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Modeling and Simulation of a Military Urban Robot Using Working Model®

by Bailey T. Haug, Timothy T. Vong, and Raymond Von Wahlde

ARL-MR-414 November 1998

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Bailey T. Haug, Timothy T. Vong, Raymond Von Wahlde
Weapons and Materials Research Directorate, ARL

Abstract

The modeling and simulation effort was conducted for the consortium led by Jet Propulsion Laboratory (JPL) as part of the Phase 1 effort of The Defense Advanced Research Projects Agency's (DARPA) BAA, "Small Unit Operations Robotics for Urban Terrain." In addition to JPL, this team included the U.S. Army Research Laboratory (ARL), Oak Ridge National Laboratory (ORNL), and the University of Southern California (USC). The ultimate goals of the modeling efforts were to verify the capabilities of the design to negotiate obstacles, to provide feedback to the design process, and to assist in the development of control algorithms. Modeling was approached with multiple tools. Initially, a kinematics analysis of the vehicle helped in understanding the motion of the microrobot and provided insights for the modeling efforts. The microrobot was then modeled in both Knowledge Revolution Inc.'s Working Model® 2-D and 3-D engineering simulation programs. Finally, Mechanical Dynamics Inc.'s ADAMS® was used to develop a full engineering model of the microrobot to include control algorithms. To date, the modeling effort has focused on the ability of the microrobot to handle stairs. This was viewed as a crucial and significant challenge that must be addressed if the vehicle is to function in urban warfare. Working Model® proved to be a powerful tool that enabled rapid examination of changes in parameters such as weight, center of gravity, strut lengths, coefficients of friction and restitution, etc. Results from the modeling effort impacted the preliminary design of the wheel and strut mobility mechanism and focused on issues that must be addressed in the final design to facilitate stair climbing. Finally, the modeling proved that the JPL/ARL/ORNL/USC team's microrobot can climb stairs using a primarily static sequence.

Acknowledgments

The authors would like to thank Gerald Lilienthal and Bret Kennedy (NASA - Jet Propulsion Laboratory [JPL]) and Stewart Young and Pete Budulas (U.S. Army Research Laboratory [ARL], Information Science and Technology Directorate [ISTD]), who all provided valuable information and/or help.

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1. Introduction

In September 1997, as a result of a Defense Advanced Research Projects Agency (DARPA) solicitation for Small Unit Operations Robotics for Urban Terrain [1], a team lead by NASA - Jet Propulsion Laboratory (JPL) was selected as one of four teams to compete in a Phase 1, 6-month effort to develop a military urban robot. Others members of this team included the U.S. Army Research Laboratory (ARL), the Oak Ridge National Laboratory (ORNL), and the University of Southern California (USC).

Figure 1 shows an artistic rendering of the JPL team's microrobot design and one possible scenario [2]. In this scenario, the robot has been tossed over a fence and has made its way through swampy terrain, through a shallow stream, and up an embankment; has climbed the 2- or 3-step threshold of the building; and has entered the building. This illustrates the mobility capability of the vehicle in traveling over a wide range of rugged terrain. Once inside the building, the military operator will make decisions on the next steps, whether to climb the stairs, map the hallway, and/or find humans or any other number of military objectives for the mission.

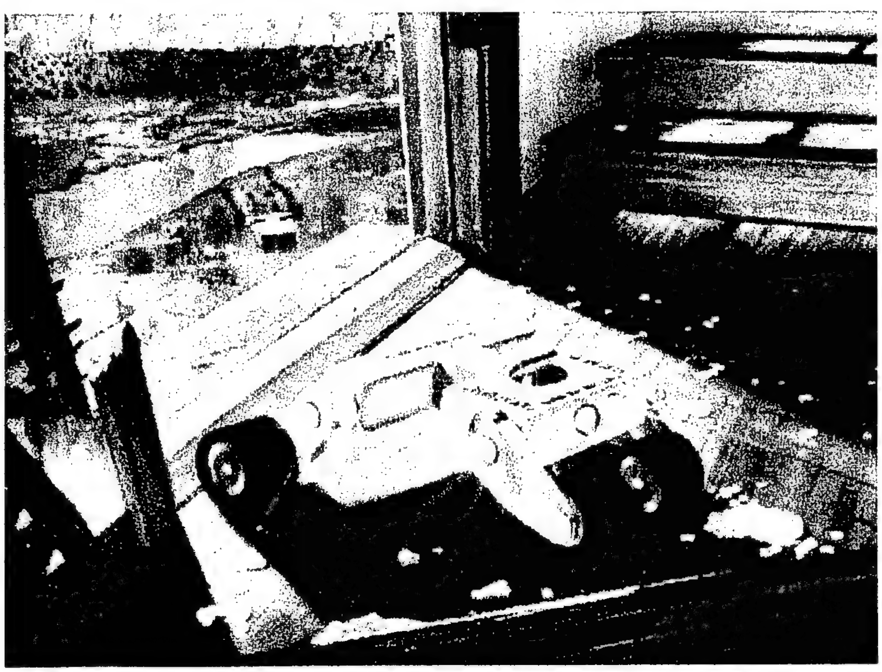

Figure 1. Artistic Rendering of JPL Lead Team's Military Urban Robot.

The microrobot used a unique strut-wheel design. Motors in the struts and gears in the "shoulders" allowed the struts to rotate relative to the "body" (Figure 2). As the front struts rotated, the front wheels could pass through cutouts in the body (Figure 3). The rear struts and wheels were placed further out from the center of the body so they could rotate without contacting the front struts and wheels. Stair-climbing was the most important driver for this design. The ability to perform this task quickly and robustly defined the success of this microrobot. This configuration is capable of rapid mobility and is agile enough to climb stairs, while maintaining a small enough size and weight to fit inside a backpack and be carried by a soldier. It was thought that a conventional wheeled or tracked configuration would be considerably larger to achieve the same mobility. The reasoning behind the use of a strut-wheel design is discussed in more detail in the Phase 1 Final Report [2].

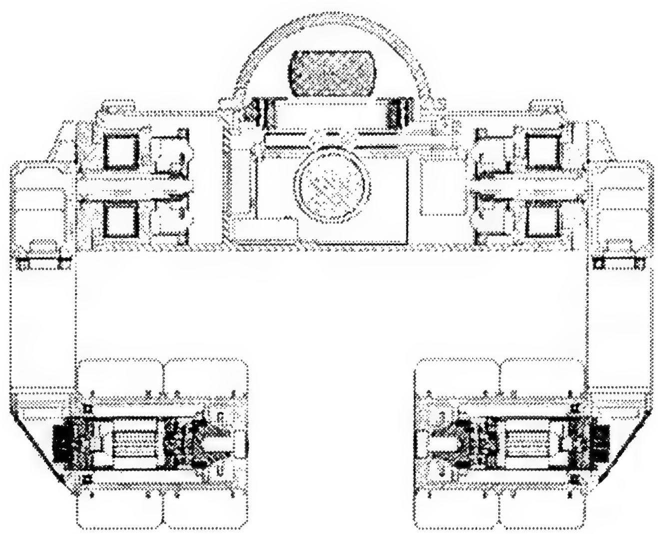

Figure 2. Front View of JPL Microrobot.

Each member of the team was responsible for various aspects of the project. One of ARL's major responsibilities was the modeling and simulation effort—the goals of which were to verify the capabilities of the robot to negotiate obstacles, provide feedback to the design process, and assist in the development of control algorithms.

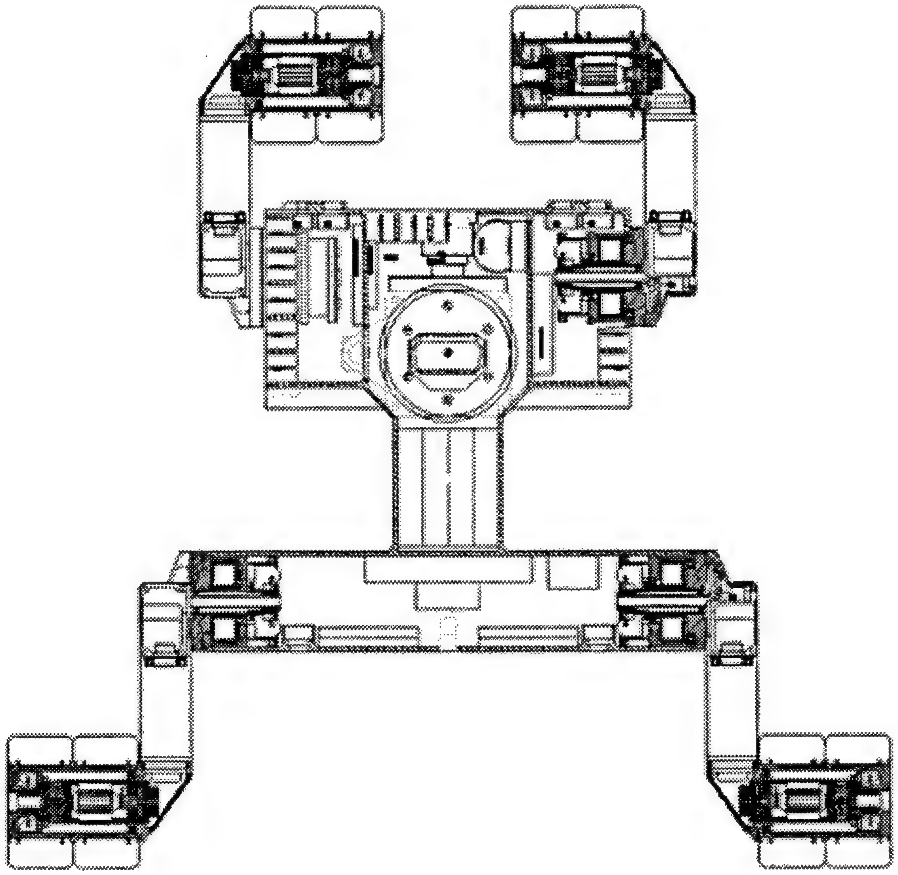

Figure 3. Top View of JPL Microrobot.

The modeling and simulation were approached with multiple tools. Initially, a simple kinematics analysis of the vehicle helped in understanding the range of motion of the microrobot and provided insight for the modeling efforts. The microrobot was then modeled in both Working Model® 2-D (Version 4.0 and 3-D, and Version 3.0 [3]). Finally, ADAMS® [4] was used to develop a full engineering model of the microrobot to include control algorithms. The modeling effort focused on the ability of the microrobot to handle stairs. This was viewed as a crucial and significant challenge that needed to be addressed if the vehicle was to function in urban warfare. This report details the modeling and simulation efforts using Working Model® and its significant contributions to the Military Urban Robot project.

2. Stair-Climbing Routine

The basic stair-climbing routine proposed by JPL is discussed in sections 2.1–2.5. The objective is to enable the microrobot to traverse steps with a series of motions that are quasi-static. That is, each intermediate configuration is a stable one that can be reached independent of the motor rates, thus not requiring feedback. It remained to be shown through dynamic modeling and simulation whether the configurations and routine were viable for climbing stairs. Working Model® was used to simulate the motion sequences described in sections 2.1–2.5. The Working Model® modeling efforts and results are discussed in detail later in this report.

2.1 Sequence 1: The Approach and Squat. In the microrobot's "cruise" configuration (Figure 4), the rear struts are rotated behind the body and the front struts are rotated forward to maximize the wheel base of the vehicle while rolling across relatively flat terrain. In this position, the struts are not long enough to place the "belly" of the body on the stair in a horizontal orientation; so, the body must be tipped. This is accomplished with a "squat" maneuver in which the rear struts are rotated forward underneath the body, while the front struts are brought to a fully vertical position (Figure 5). The amount that the rear wheels are moved forward in relation to the body governs how high the "chin" of the rover is raised. The final height can either be a variable or fixed value, depending on how well the rise of the stair is known. If the rise is known, the rear wheels will be left as far back as possible for stability. In order to properly register itself with the stair, the rover continues to drive its wheels until feedback sensors (either in the body or in the struts) tell it that it is in full contact with the stair.

2.2 Sequence 2: The Push and Slide. With its chin set on the stair, the rover now drives forward, rotating the front struts back as it goes, until the front wheels rest on the stair. This maneuver is shown in Figures 6 and 7.

2.3 Sequence 3: The Tuck and Fold. Due to wires that cross the shoulder joint and the difficulty of implementing slip rings, it was necessary to limit motion of the shoulders to ±180° rather than allow them to rotate a full 360°. In order to get the back wheels onto the stair,

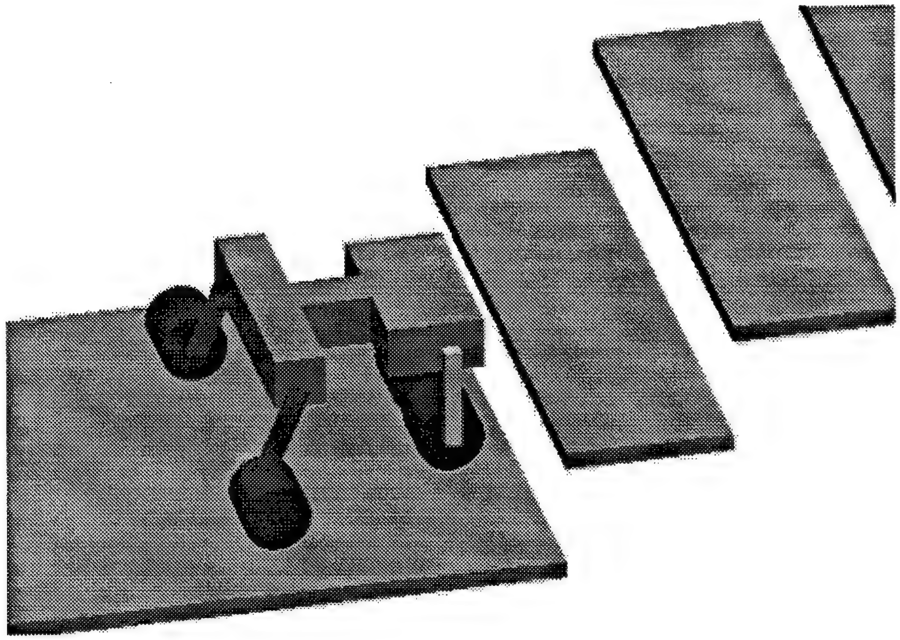

Figure 4. Stair-Climbing Sequence 1: The Approach.

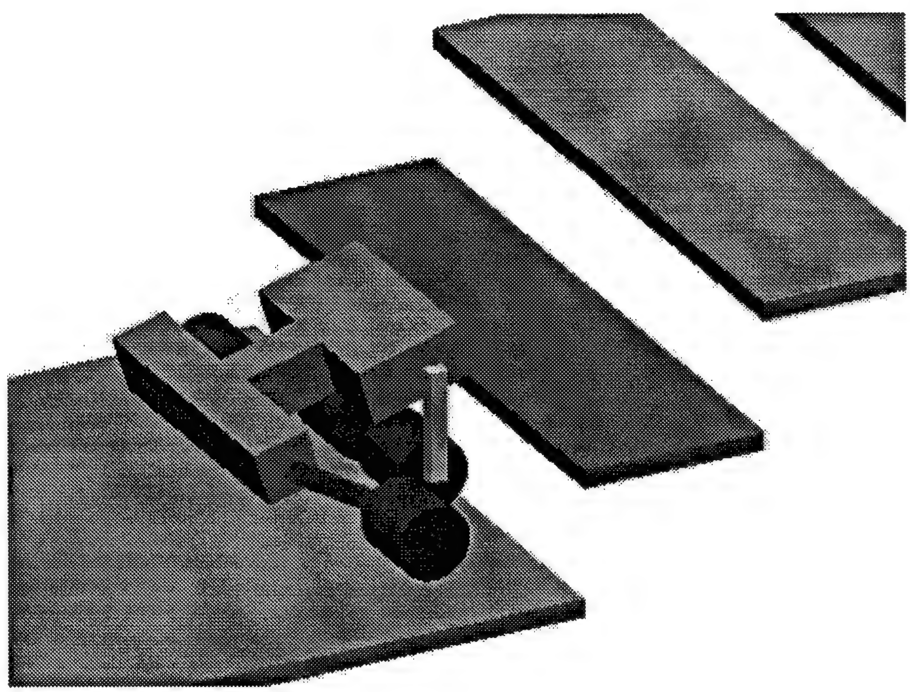

Figure 5. Stair-Climbing Sequence 1: The Squat.

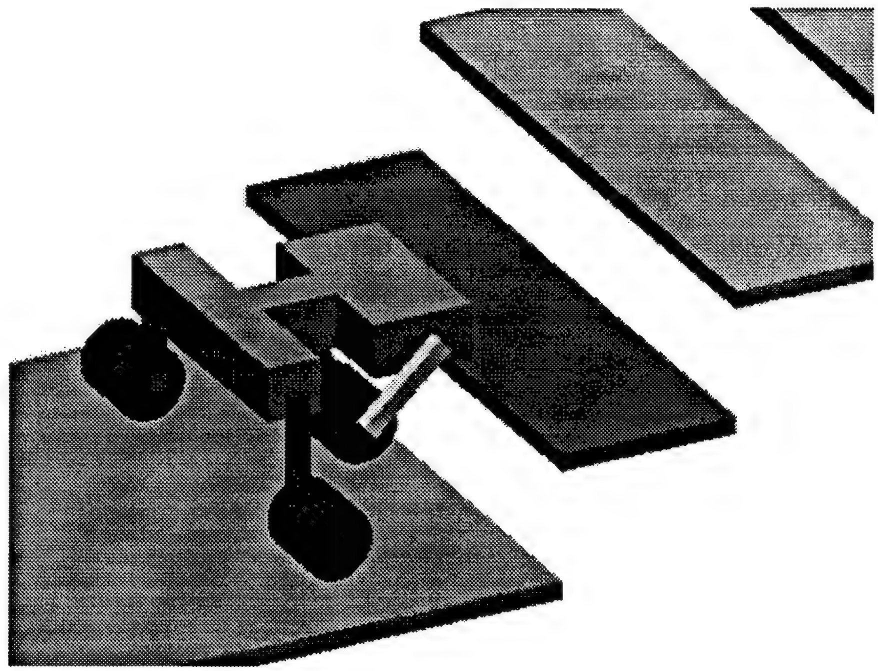

Figure 6. Stair-Climbing Sequence 2: The Push.

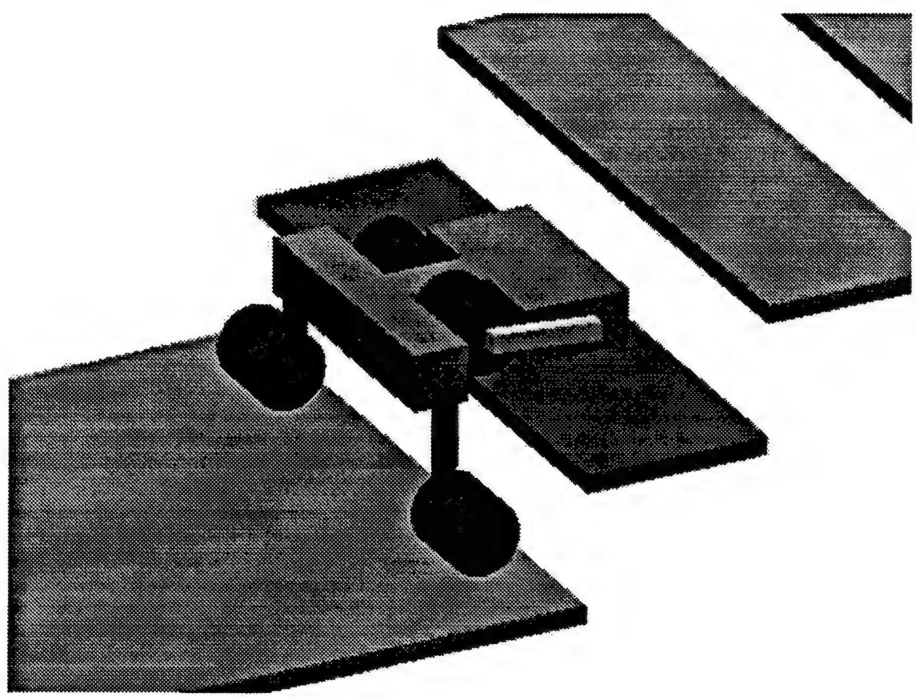

Figure 7. Stair-Climbing Sequence 2: The Slide.

they must be tucked under the body rather than swung around over the top. To accomplish this move, the front struts are rotated forward relative to the body. Since the center of gravity of the vehicle is forward of the front wheels, the body pivots upward, allowing room to pull the rear wheels under the body. The front struts then reverse direction, placing the body in a horizontal position again. Figure 8 illustrates the body tilted up, while Figure 9 shows the fully folded rover.

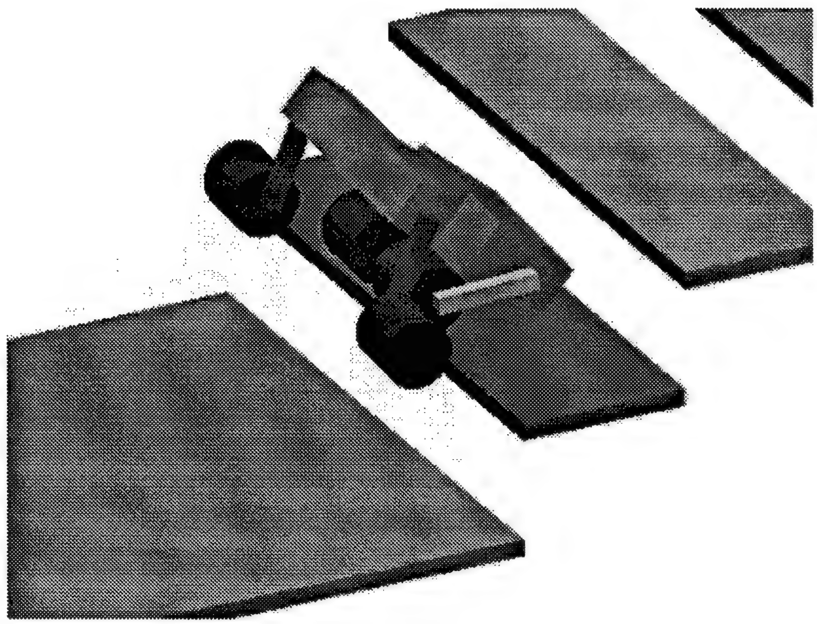

Figure 8. Stair-Climbing Sequence 3: The Tuck.

2.4 Sequence 4: The Raise. The rover must now move back into a standing position. Because of the unique design of the rover, the wheels and struts are free to pass by each other. This ability allows the rover to raise itself by simultaneously moving the front struts forward and the rear struts backward. An inherent complication of this maneuver is that, at some point in the motion, all the axes of the wheels will be collinear, creating an "inverted pendulum," as shown in Figure 10. However, the modeling effort indicated that, with some care, the vehicle can be expected to stand up from the folded position. One reason is that the tires do not form a line contact with the stairs; rather, there is a tire contact patch. If, during the raise, the vertical projection of the center of gravity can be kept within or very close to the tire contact area, then

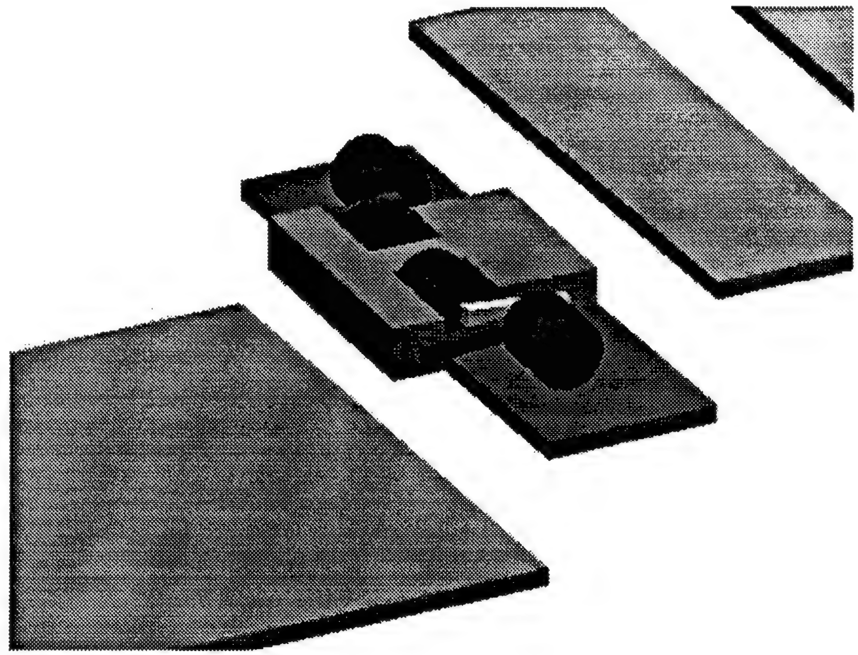

Figure 9. Stair-Climbing Sequence 3: The Fold.

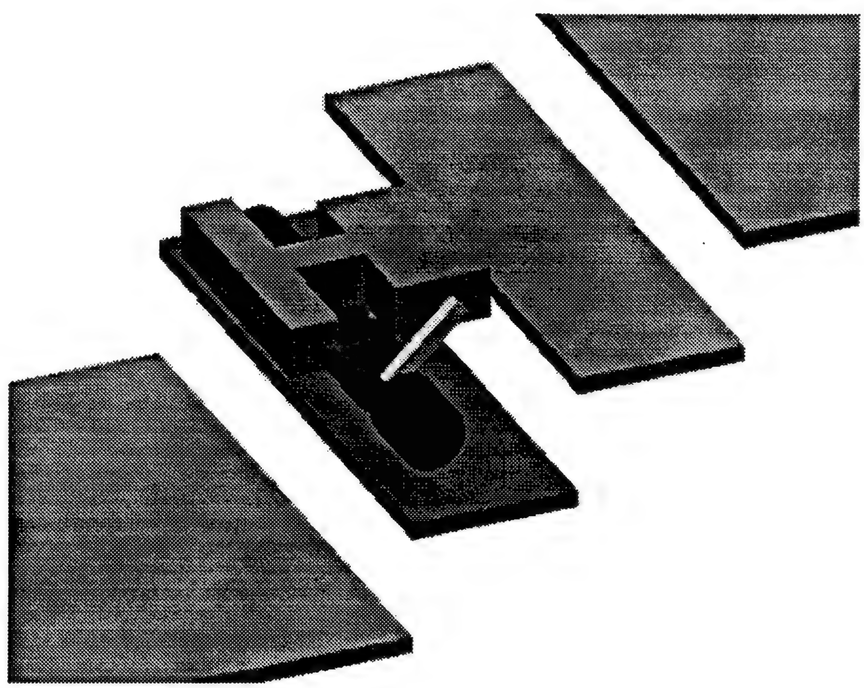

Figure 10. Stair-Climbing Sequence 4: The Raise.

the upsetting torque, and therefore the angular acceleration, is kept relatively small. The motion of the vehicle standing up was also successfully demonstrated in an ADAMS® simulation, despite the static instability of the inverted pendulum.

2.5 Sequence 5: Repeat. Once standing, the rover can repeat steps 1–4 to climb the next stair (Figure 11). It is projected that the entire sequence will take less than 10 s per stair, and maybe as little as 5 s. At these speeds, a standard flight of stairs would take on the order of 2 min to climb—a time certainly within the restrictions imposed by urban combat.

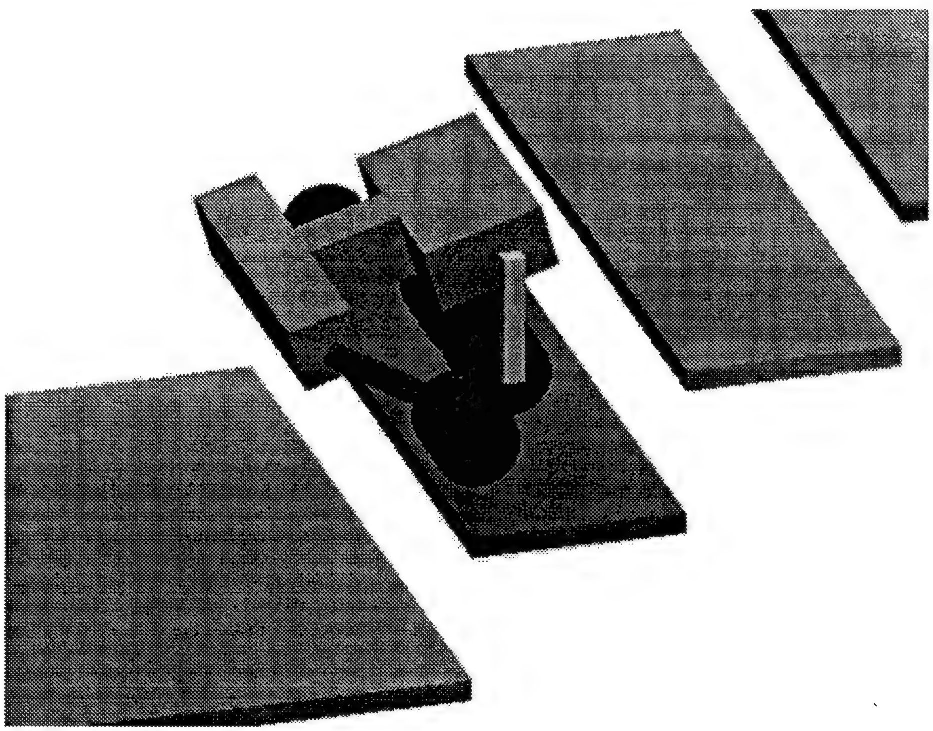

Figure 11. Stair-Climbing Sequence 5: The Repeat.

3. Simulation

The stair-climbing sequence was modeled in both Working Model® 2-D and 3-D. The 2-D and 3-D models are shown in Figures 12 and 13, respectively. A component list is shown in

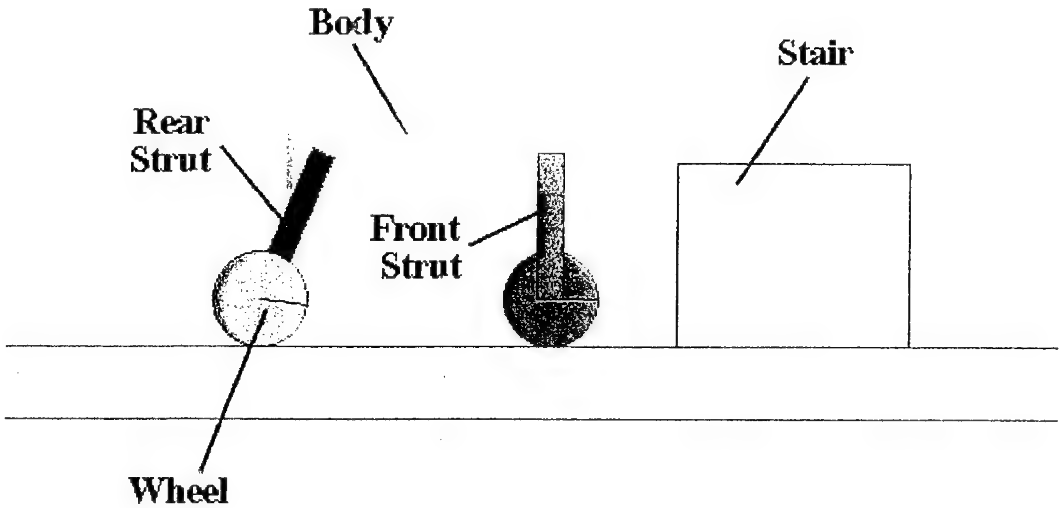

Figure 12. Working Model® 2-D.

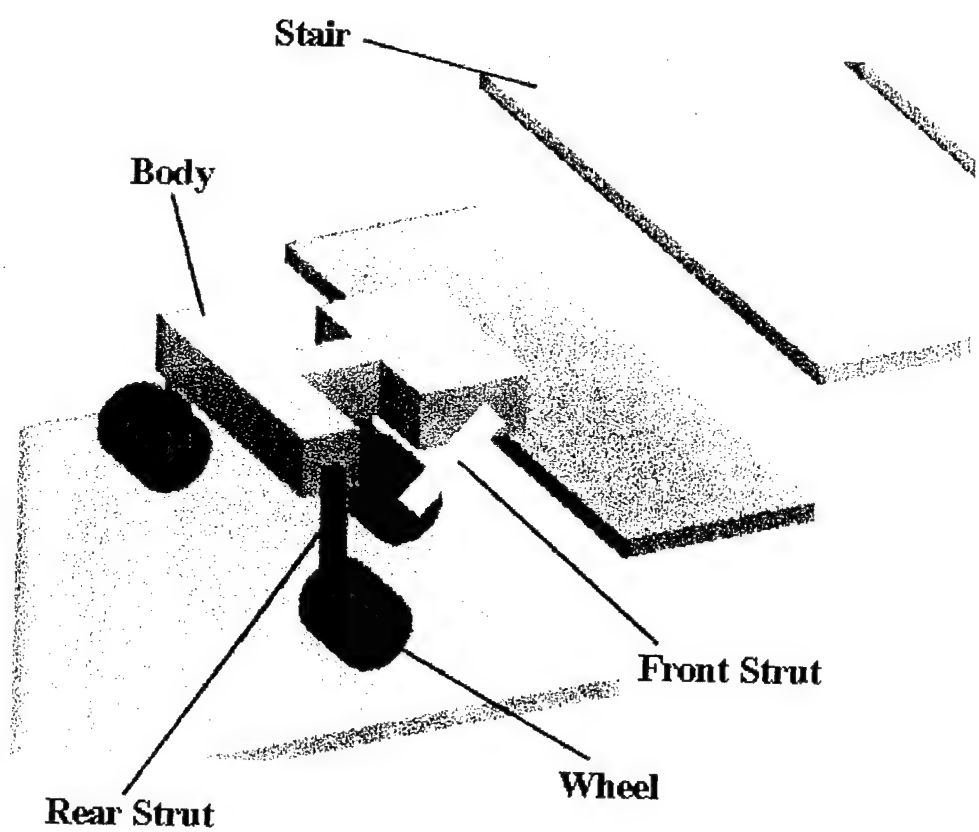

Figure 13. Working Model® 3-D.

Table 1. The values in the table reflect the prototype microrobot's dimensions, overall weight, inertial properties, mechanical abilities, and constraints as closely as possible.

Table 1. Working Model® Component List.

Component	Weight (lb)	Quantity	Basic Dimensions (in)	Total Weight (lb)	Coeff. of Friction	Coeff. Of Restitution
Body	17.75	1	$15.5 \times 13 \times 3$	17.75	0.25	0.1
Front Strut	1.06	2	$6 \times 1 \times 0.875$	2.12	0.5	0.1
Rear Strut	1.06	2	$6.5 \times 1 \times 0.875$	2.12	0.5	0.1
Wheels	2	4	2-in radius $\times$ 4	8	0.5	0.1
Stairs	N/A	4	$36 \times 10 \times 1$	N/A	0.5	0.1
Revolute Motor	N/A	8	N/A	N/A	N/A	N/A
Revolute Pin	N/A	8	N/A	N/A	N/A	N/A

3.1 Software and Hardware Description. Working Model® 2-D and Working Model® 3-D are commercially available software made by Knowledge Revolution Inc. Working Model® 2-D provided some advantages over the version of Working Model® 3-D that was used in this simulation. These included somewhat greater ease in model creation, the ability to read Microsoft® Excel Spreadsheets as input to the revolute motors, and the ability to display the vehicle center of gravity.

The simulation software was loaded and running on a Microsoft® Windows-based-operating system computer. The computer hardware has a Pentium II® with an MMX Technology processor running at 200-MHz speed and 64 MB of RAM.

3.2 Model Description and Boundary Conditions. The basic assumptions and simplifications made for each component are described in the following sections and shown in

Table 1. The values in the table reflect, as close as possible, the prototype microrobot's dimensions, overall weight, inertial properties, mechanical abilities, and constraints. Working Model® allows rigid-body collisions between components using the coefficient of restitution. The coefficient of restitution is defined as the magnitude ratio of the relative velocities of the colliding bodies immediately before and after collision [3]. The coefficient can range from 0 (perfectly plastic impact) to 1 (perfectly elastic impact). In the 2-D model, collisions between the wheels, struts, and body were turned off to replicate the unique strut-wheel design movements. In the 2-D model, there exist only one front and one rear strut/wheel subassemblies; the weights of the struts and wheels were doubled in order to equal the overall mass of the 3-D model. While this required more torque from the motors so they could rotate the wheels and struts at a desired rate, the static stability of each configuration could be evaluated. Collisions of the body, struts, or wheels with the steps were permitted. When two bodies are in contact with differing coefficients of restitution and friction, the lesser value of either coefficient is used. The dynamic model also had gravity (9.81 m/s^2) acting on it.

3.2.1 Body. The overall weight of the body included the weights of the expected sensors (forward-looking infrared [FLIR] camera, infrared [IR] sensors, charged coupled device [CCD] cameras, and acoustic arrays), shoulder motor gears, batteries, etc., that were to be a part of the body. Since the sensor and other component locations were not finalized, the body center of gravity location was varied as part of the modeling effort. The center of gravity of the body for this configuration was optimized to be 8 in (203 mm) from the rear and 1 in (25 mm) down from the centerline. This was necessary so the microrobot would be stable in the squat configuration. The body was permitted to make contact with the steps. A coefficient of friction of 0.25 was used to make the push maneuver easier. A coefficient of restitution of 0.1 was probably too low a value to use, but the sequence is not dependent on it.

3.2.2 Front Struts. Weight and length duplication were the major considerations for the front struts. The weight of this component included the shoulder motors. The final strut length, the distance between the front shoulder joint axis and front wheel axis, was 6 in. During modeling, this component was not looked at for optimization due to time constraints and related

costs. A hardware prototype was already being manufactured parallel with the modeling efforts, and a significant change in the front strut length would require corresponding changes in the body. The front struts were permitted to make contact with the steps. A coefficient of friction of 0.5 was used. A coefficient of restitution of 0.1 was probably too low a value to use, but there was minimal contact between the front struts and steps.

3.2.3 Rear Struts. The design of the vehicle allowed significant modification of the rear strut length with no reconfiguration of the body. As a result of the modeling efforts, a strut length of 6.5 in from the shoulder joint axis to rear wheel axis was selected. The weight of this component included the shoulder motors. The optimization of this component is discussed later in the report. The rear struts were permitted to make contact with the steps, although this did not occur in the stair-climbing sequence. Even so, a coefficient of friction of 0.5 and a coefficient of restitution of 0.1 were used.

3.2.4 Wheels. The front and rear wheels were the same. The weight of the wheels included the motors to drive them. Minimal optimization was performed on the wheels. The coefficient of restitution was reduced to 0.1 to minimize the bounce of the vehicle. This could be accomplished with foam-filled rubber tires. The coefficient of friction was set to 0.5. This value was chosen as an "average" performance, based on the literature listings for the performance of car tires on dry pavement in the 0.4–0.7 range. These coefficients could be furthered optimized or changed to reflect the "actually" achieved values.

3.2.5 Revolute Motors. There were eight revolute motors in the model—one for each of the strut/wheel and strut/shoulder connection. The motors were primarily given angular velocities to control them; although, they can also be described by torques, orientations, or accelerations. Working Model® considers the motors to be weightless, but their approximate weights were accounted for in the other component's weights. The shoulder motors were limited to maximum angular rates of 45°/s. The angular displacement of each shoulder motor was limited to ±180°. The wheel motors were limited to maximum angular rates of 1,080°/s. This would give a maximum vehicle speed of 1 m/s. The wheel motors were not limited in rotation angles. The motor speeds were controlled in the Working Model® simulations by the modeler changing

"buttons" and "sliders" interactively. The motors could also be reversed or turned of interactively and variably by relating them to the operation of another motor (e.g., on/off, on/on, and/or forward/reverse relations).

3.2.6 Revolute Pins. There were eight revolute pins in the model—one for each revolute motor. The pins were activated only when their related motors were turned off, allowing the components to rotate freely at their respective joints. These are also weightless components.

3.2.7 Stairs. The major characteristics of the stairs are the rise, run, and coefficient of friction. The model started with a rise of 7.5 in and run of 10 in, but this proved to be too difficult a task for this phase, given the constraints of time and the fact that only the rear strut length and the system center of gravity could be changed. The decision was made to go with a 7-in rise stair, which is less stringent but still representative of the expected stairs. A parametric study is needed for the rise and run of stairs vs. optimized microrobot designs.

Collisions between the stairs and all of the other components were permitted. The coefficient of friction was 0.5. The stairs also had open backs—a more difficult challenge than a closed-back stair. When folded, the microrobot is short enough to clear the lip of the next step and fall through the back if driven straight through. During modeling, the robot speed was adjusted interactively so it would stop before falling through. The stair rise (7 in) was formed by anchoring each step component to the background at the correct world coordinates so that the vertical coordinate difference was equivalent to the stair rise.

4. Results and Discussion

The initial objective to traverse the steps with a series of "quasi-static" motions was largely realized, with the exception of the "inverted pendulum" move mentioned in section 2.4. The following sections describe the design feedback generated by the modeling tools.

4.1 Sequence 1: The Approach and Squat. As can be seen in Figure 5, the placement of the center of gravity is critical for stability. An empirical envelope for the location of the center

of gravity that allowed the rover to move from the cruise position to the squat position without falling over was determined. Modeling showed that the center of gravity location of the body needed to remain between the front and rear wheel axes at all times to achieve quasi-static positions. The parameters that controlled this were the rear strut length and the component weights and distributions. A shorter rear strut would widen the wheel base. A more forward and lower center of gravity was better. An optimal body center of gravity location was found for the current microrobot configuration and stair size. More modeling would be required to develop an optimal center of gravity location, based on an optimal microrobot configuration that would allow it to climb more challenging stairs.

4.2 Sequence 2: The Push and Slide. The primary difficulty with this move is the reaction force created during the push performed between Figures 5 and 7. Beveling the lower front corner of the body will make placing the chin on the step easier. However, frictional force is the primary obstacle. Because it is unknown what type of stair tread the rover may encounter, this move must be planned for a variety of surfaces (e.g., concrete, wood, metal, carpet, or steps with antislip strips). The computer model allowed the coefficient of friction between the body and step to be adjusted, and it indicated the need to minimize the friction of the body on the step. The coefficient of friction of the body was varied between the values of 0.5–0.25. Modeling determined that the coefficient of friction should be no more than 0.25. Some possible means of reducing the coefficient of friction are coating the belly with low frictional material like Teflon and installing passive wheels or bearings on the underside.

The simulation also helped determine that a distance of 6.5 in (16.5 cm) between the axes of the rear shoulders and wheels is needed to move the body up onto a 7-in (17.8 cm) step, based on the current design configuration. If the rear struts were shorter, the microrobot would not be able to push itself forward enough to engage the front wheels on the next step. If the rear struts were much longer, it would affect the ability of the microrobot to achieve quasi-static positions due to the reasons mentioned previously in section 4.1.

4.3 Sequence 3: The Tuck and Fold In the rover's current configuration, with the front wheels firmly placed on the step approximately one half a wheel radius from the edge (1 in

[25 mm]), modeling determined that this pivot maneuver requires a minimum step run of 10 in (25 cm) for a closed-back step. This is shown in Figures 8 and 9.

4.4 Sequence 4: The Raise. As has been mentioned and shown in Figure 10, the front and rear wheels become collinear, forming a type of inverted pendulum during the maneuver between Figures 9 and 11. This is the only point in the climbing sequence that is not statically stable. Various attempts were made to avoid this situation, such as first moving the struts on one side through the collinear configuration, then moving the other side. However, Working Model® indicated that, with the proper strut rates, the body could be lifted relatively straight up, and the wheels could be made to pass through the unstable point before the body had time to pivot rearward or forward. ADAMS® demonstrated that optimal strut rates that minimize deviation of the center of gravity from its intended vertical path can be found. This will allow a preprogrammed, feed-forward, control command that causes the rover to perform this maneuver without relying on feedback. Future modeling efforts could explore taking advantage of the onboard orientation sensors as feedback in a closed-loop control function. Another possibility is to develop a modified configuration that will enable the microrobot to avoid the inverted pendulum altogether.

5. Conclusions

The computer simulation of the stair-climbing proved to be a powerful tool. It allowed for rapid examination of changes in microrobot parameters such as weight, center of gravity, strut lengths, coefficients of friction, etc. This enabled the level of difficulty (obstacles) of the simulation environment to be easily adjusted. The modeling effort included only stair-climbing but could be expanded to include other military operations in urban terrain (MOUT) obstacles in future modeling efforts. The modeling also proved that the JPL/ARL/ORNL/USC team's microrobot can climb stairs, using a primarily quasi-static sequence. In addition, the modeling ensured that the torque needed to rotate the struts and wheels at the desired rates is within the range of the commercially available motor/gear head combinations to be used. Future modeling effort could provide a progressively more detailed simulation, driving the design to an optimal configuration that can overcome most conceivable obstacles in a MOUT environment.

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4. Mechanical Dynamics, Inc. *User's Manual for ADAMS®*, 1997.

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13. ABSTRACT *(Maximum 200 words)* The modeling and simulation effort was conducted for the consortium led by Jet Propulsion Laboratory (JPL) as part of the Phase 1 effort of The Defense Advanced Research Projects Agency's (DARPA) BAA, "Small Unit Operations Robotics for Urban Terrain." In addition to JPL, this team included the U.S. Army Research Laboratory (ARL), Oak Ridge National Laboratory (ORNL), and the University of Southern California (USC). The ultimate goals of the modeling efforts were to verify the capabilities of the design to negotiate obstacles, to provide feedback to the design process, and to assist in the development of control algorithms. Modeling was approached with multiple tools. Initially, a kinematics analysis of the vehicle helped in understanding the motion of the microrobot and provided insights for the modeling efforts. The microrobot was then modeled in both Knowledge Revolution Inc.'s Working Model® 2-D and 3-D engineering simulation programs. Finally, Mechanical Dynamics Inc.'s ADAMS® was used to develop a full engineering model of the microrobot to include control algorithms. To date, the modeling effort has focused on the ability of the microrobot to handle stairs. This was viewed as a crucial and significant challenge that must be addressed if the vehicle is to function in urban warfare. Working Model® proved to be a powerful tool that enabled rapid examination of changes in parameters such as weight, center of gravity, strut lengths, coefficients of friction and restitution, etc. Results from the modeling effort impacted the preliminary design of the wheel and strut mobility mechanism and focused on issues that must be addressed in the final design to facilitate stair climbing. Finally, the modeling proved that the JPL/ARL/ORNL/USC team's microrobot can climb stairs using a primarily static sequence.

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military urban robot, dynamic modeling and simulation, and Working Model® 2-D and 3-D

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